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Potential use of lignosulfonate for expansive soil stabilisation

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Abstract

This study involved the laboratory evaluation of the effectiveness of lignosulfonate (LS) admixture in improving engineering properties (i.e. swell potential, unconfined compressive strength, durability, compaction characteristics, permeability, consolidation characteristics and shrinkage behaviour) of a remoulded expansive soil. Standard geotechnical laboratory tests performed on untreated and LS-treated soil specimens compacted at optimum moisture content and maximum dry unit weight showed significant and consistent improvements in the engineering properties of the soil. The swell potential of the soil decreased by 23% while maintaining its ductility and pH value. The improved soil resistance to repeated freeze-thaw/wet-dry cycles was also observed in the LS-treated specimens. Likewise, the compressive strength, consolidation characteristics and shrinkage limit improved appreciably. However, the compaction characteristics and permeability of the treated soil remained relatively unchanged. With over 50 Mt of global annual production of LS, the successful use of LS as an alternative admixture for expansive soil stabilisation provides viable solutions to the sustainable use of the lignin by-products from paper manufacturing industry.

POTENTIAL USE OF LIGNOSULFONATE FOR EXPANSIVE SOIL STABILISATION

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Abstract

This study involved laboratory evaluation of the effectiveness of Lignosulfonate (LS) admixture in improving the engineering properties (i.e. swell potential, unconfined compressive strength, durability, compaction characteristics, permeability, consolidation characteristics, and shrinkage behaviour) of a remoulded expansive soil. Standard geotechnical laboratory tests performed on untreated and LS treated soil specimens compacted at optimum moisture content and maximum dry unit weight showed significant and consistent improvements in the engineering properties of the soil. The swell potential of the soil decreased by 23% while maintaining its ductility and pH value. Improved soil resistance to repeated freeze-thaw/wet-dry cycles was also observed in the LS treated specimens. Likewise, the compressive strength, consolidation characteristics and shrinkage limit improved appreciably. However, the compaction characteristics and permeability of the treated soil remained relatively unchanged. With over 50 million tonnes of global annual production of LS, the successful use of LS as an alternative admixture for expansive soil stabilisation provides viable solutions to the sustainable use of the lignin by-products from paper manufacturing industry.

KEYWORDS: soil stabilization, strength and testing of materials, sulfate-based cement

Introduction

Expansive soils are known to exhibit adverse volume change behaviour in response to moisture variation. In Australia, heavily populated areas in many cities are underlain by expansive soils (Richards et al.1983; Kapitzke and Reeves 2000). The volumetric instability of these soils causes billions of dollars in damage every year to buildings, roads, pipelines, and other structures (Richards 1990; Mitchell 1980). Considine (1984) reported on the average, that more than 50,000 houses crack each year in Australia, which accounts for approximately 80% of all housing insurance claims. In fact, Snethen (1986) called expansive soils the "hidden disaster," because damages caused by these soils are not dramatic as natural disasters as they only cause property damage without fatalities.

Several techniques for minimizing the effects of expansive soils on civil infrastructure have been developed over the years. Among these numerous techniques, the use of traditional chemicals (i.e. lime and cement) has gained global acceptance for decades. These additives can be very effective, though not without inherent health and safety concerns such as increase in soil pH upon treatment, brittle failure, compromising groundwater quality, and poor performance in sulfate rich soil due to the formation of expansive minerals; (e.g. ettringite) and thaumasite (Pupalla et al. 2004), thus the global interest for a more environmentally benign alternative admixture.

Many industrial by-products (e.g. fly ash, coal wash, and steel slag) have been used as soil stabilizing agents (e.g. Indraratna et al. 2008, Tassalotti et al. 2015; Heitor et al., 2016). Indraratna et al. (2008) reported that LS admixture reduced the coefficient of soil erosion and significantly increased the critical shear stress of a silt clay soil. Nicholls and Davidson (1958) reported that LS stabilizer contributed to a rapid increase in the shear strength of soil with an increase in the length of air curing. Similarly, Chen et al. (2014) reported on the improved shear strength behaviour of sandy silt treated with LS admixture. Of interest in this study is the use of a waste by-product known as Lignosulfonate (LS) from the paper manufacturing industry in stabilizing expansive soil. With a global production estimated at 50 million tonnes (Gandini and Belgacem 2008), it is envisaged that the disposal of this by-product could be sustained through its application in geotechnical engineering. The effectiveness of LS in altering the shrink/swell potential, freeze-thaw/wet-dry durability, unconfined comprehensive strength, compaction characteristics, permeability, consolidation, and soil pH of a remoulded expansive soil was assessed.

Material

The laboratory experiments were carried out on Gunnedah clay collected from Queensland

Australia. The liquid limit of the soil is 91% with a plasticity index of 51%. With a percent swell 6% under a 7kPa seating pressure, the soil can be classified as a "high" expansive soil in accordance to Seed et al. (1962) classification scheme. The activity of the soil was 1.42 and a shrinkage limit of 9% was determined. These values agree with the "high" expansive class (shrinkage limits of 7 – 12%) per Holtz and Gibbs (1956) classification scheme, while Skempton (1953) reported that activity greater than 1.25 is indicative of an expansive soil. The particle size distribution of the soil showed that it is composed of 35.4% clay, 55.6% silt and 10% sand, respectively (Fig 1). The detailed physico-chemical properties of the soil can be found elsewhere (e.g. Alazigha et al. 2017).

The pH of untreated soil fluid, 2% LS and 2% cement treated specimens were determined after 7 days of curing. The results (average of 3 tests) were found to be 7.43, 7.17 and 9.65 respectively. The pH of the soil after LS addition remained practically unchanged, possibly because the soil ions acted as an acid to form $H^{+}_{(aq)}$ with water, while the LS ions acted as a base to give $OH^{-}_{(aq)}$ with water, so they effectively neutralised each other (Theng, 2012).

Moreover, the unchanging soil pH could also be related to the very small amount of LS required to stabilize the soil (2% by dry weight of soil). In contrast, 2% cement treated soil shows increase in alkalinity (7.43 to 9.65) which could be detrimental to flora and fauna or could affect the longevity of reinforced concrete and steel frame structures and/or pollute groundwater.

Testing program

The soil was collected, dried, pulverized, and sieved through 1.18mm aperture sieve. An amount of distilled water equivalent to the optimum moisture content was mixed with an aliquot of the dry soil and allowed to mellow in sealed double plastic bags for 24hr prior to specimen preparation for each test. For treated specimens, 2% LS by dry weight of soil was added into the required amount of water prior to mixing with the dry soil. Alazigha et al. (2016) investigated the variation of liquid limit (LL) and plasticity index (PI) characteristics based on the percentage of LS admixture. The addition of LS resulted in a decrease in the LL (91 to 76%), and a slight increase in the plastic limit (40–44%), prompting a significant 37% reduction in the soil PI index (51 to 32%) at 2% addition. The change in PI was attributed to the transformation of the soil particles from a discrete state to non-discrete particles. However, increasing the LS content beyond 2% threshold resulted in adverse soil characteristics. For example, at a 4% application rate, the LL decreased to 80% only, with a corresponding increase in the plastic limit from 40 to 41%, hence, 2% LS content was considered as the optimum for the soil. In addition, the swell percent of the soil was investigated based on %LS content. The results indicated maximum swell percent reduction at 2% LS application.

After 24 hours, an aliquot of the soil-water mix was collected and statically compacted into 50mm diameter x 20mm height consolidometer ring at a rate of 1mm/min to attain the maximum dry unit weight (13.1kN/m^3). The ASTM D4546 (ASTM, 2008) was adopted for testing the percent swell of the soil with a seating load of 7kPa which is a more reasonable pressure a founded structure exerts on an expansive soil (Seed et al. 1962). At the end of the one-dimensional swell test, volumetric shrinkage test was conducted on the specimens in accordance with Briaud (1998) while AS1289 3.4.1 (Standards Australia, 2000) was adopted for linear shrinkage test. The durability of the test specimens (Freeze-thaw and wet-dry) was also checked. An appropriate mass of the mix was statically compacted into a 115mm height x 105mm diameter mould to predetermined dry unit weight (13.1kN/m^3) and tested for durability in accordance with ASTM D560 (2003) and ASTM D559 (ASTM, 2003). However, the application of wire scratch brush was neglected and specimens were submerged in water bath for an hour only.

The method for preparation and testing of compacted materials recommended in AS 5101.4 (Standards Australia, 2008) was adopted for the determination of unconfined compressive strength (UCS) of samples. To establish the compaction characteristics, Standard Proctor compaction tests were performed in accordance with AS 1289.5.1.1 (Standards Australia, 2003) using a compaction effort of 596kJ/m^3. The consolidation behaviour of untreated and 2% LS treated samples were determined as per ASTM D 2435M (2011). To evaluate the effect of LS on soil pH, the AS 1289.4.3.1 (Standards Australia, 2000) was used to measurement soil-water and soil-water-LS solutions.

Results and Discussion

Compaction characteristics and swelling behaviour

The impact LS had on the densification of the remoulded expansive soil was investigated by establishing the moisture content-dry unit weight curves for the untreated soil and soil treated with 2% LS using a Standard Proctor compaction effort, i.e.590 kJ/m^3 (Fig 2). There was a slight tendency for both the optimum moisture content (OMC) and maximum dry unit weight (MDUW) to decrease when LS was added. The compaction curve for the soil treated with LS was determined after a weighted average of three Standard Proctor tests. The MDUW and OMC for 2% LS treated soil was 12.9kN/m^3 and 36%, respectively, as opposed to 13.1kN/m^3 and 37% for untreated soil. Therefore, the marginal decrease in OMC and MDUW could be associated with the presence of LS admixture which might have initiated the flocculation of soil particles through adsorption and cation exchange mechanisms. The structure of the compacted soil (treated with LS and untreated) was examined using a scanning electron microscope (SEM) JEOL JSM-6490LA housed at the microscopy facility of the University of Wollongong. This SEM can operate at low vacuum, which allows the testing of specimens in a moist condition, thus avoiding undesirable microstructural damage that can results from the drying process. The flocculation of soil particles upon compaction that resulted from the LS addition can be easily observed in the modified SEM micrographs shown in Fig 3 (Alazigha et al. 2016). This agrees with previous studies conducted by Puppala and Hanchanloet (1999) in which sulphuric acid and lignosulfonate chemicals (SA-44/LS-40, or DRP) were mixed and used to improve soft subgrade soil.

To understand the relationship between compaction characteristics and the corresponding percent swell of the soil, selected untreated and LS treated specimens obtained from points 1-5 (Fig 2) were tested for one dimensional swell test. Within the range defined by typical end-product specifications of compacted fills (shaded area in Fig. 2) for which a moisture range of $\pm$ 2% of OMC and a minimum 95% of maximum dry unit weight is targeted, it can be observed that the swell magnitude decreased 23% upon treatment. Furthermore, Fig. 2 also indicated that as the initial moisture content decreased, the percent swell increased. However, this progressive increase in the percent swell due to decreasing initial moisture content is counter-balanced by the decreasing initial dry unit weight of the soil. In other words, as the dry unit weight of the soil decreases, the amount of intrinsic expandable minerals available to swell decreases creating an opposing effect with the soil's tendency to swell due to the decreasing initial moisture content. The tendency to increase the swell magnitude due to decreasing initial moisture content and increasing initial dry unit weight is observed across the compaction plane, except for very low water contents, referred herein as the equilibrium range of moisture content. In this range, the combined effect of the water content and dry unit weight variation counter balanced each other and thus the slope of the swell curve tends to zero, which indicates that the swell magnitude obtained in this range is independent of the initial compaction state.

The effect of the initial dry density on the shrink-swell behaviour

Fig 4 illustrates the shrink-swell behaviour of untreated expansive soil and that treated with LS. The percent swell decreased with increasing content of admixture up to 2%, resulting in a shape referred herein as the ~~cone~~ range of stabilisation. This ~~cone~~ range is divided into three sections based on the magnitude of the percent swell of the specimens and the associated dry unit weight (DUW). These sections are, the 'low' compaction range 75-80% of the maximum dry unit weight (MDUW) of the soil, 'medium' is between 80%-95% of MDUW and 'high' corresponds to 95-100% of MDUW. The magnitude of swell in the first segment, representing the 'low compaction range, is barely altered with the addition of LS, but as the dry unit weight of soil increased so does the efficacy of LS in decreasing the percent swell. Within the medium compaction range, there is an appreciable reduction in the magnitude of swell, but a further increase in the dry unit weight of soil, i.e. to the "high DUW range", the reduction in the percent swell is such that 1% application of LS equals the reduction observed by 2% LS addition within the 'low compaction range.

Similarly, the magnitude of soil shrinkage decreased with an increasing initial dry unit weight of soil, while the incremental addition of LS showed a continued decrease in shrinkage. After 2% was added, the potential to shrink was almost negligible, this is more evident within the high compaction range. The practical implication is that the effectiveness of LS to stabilise expansive soil improves with increasing initial dry unit weight of soil. It is therefore suggested that soil treated with LS to be compacted at OMC and in the 95-100% MDUW range in order to maximise its potential in reducing the magnitude of post-compaction volumetric changes (swell and shrinkage). The effective packing of soil particles achieved in the "high' DUW region coupled with the stabilisation effect introduced by the LS admixture prevented the soil from shrinking despite changing moisture content.

Volumetric shrinkage after swelling

To evaluate the magnitude of the volumetric shrinkage of the soil specimens after swelling, at the end of the one-dimensional swell test, the specimens were dried at room temperature in stages and the associated variation in dimensions and mass were recorded as recommended by Briaud (1998). The specimens were removed from the oedometer, weighed, and the dimensions measured and recorded. They were allowed to dry at room temperature while measurements were taken at regular intervals until constant mass was reached, and then placed inside an oven set to 105^0C, after which their final weight and dimensions were measured and recorded. The results obtained for volumetric shrinkage of the specimens having different moisture contents are shown in Fig 5. At high moisture contents (w= 25 -50%), a linear relationship between volumetric strains and moisture content is evident. This is consistent with the findings reported in Sarkar et al. (2000). The slope defined in this range is referred to as the shrink modulus (Ew). The Ew value for untreated, specimens treated with 2% LS, and with 2% cement was 1.19, 1.41 and 1.48, respectively. This indicates that samples treated with 2% LS and those treated with cement exhibit less shrinkage (i.e. larger Ew) than the untreated specimens. Final drying results indicated 20, 17.4, and 16.8% volumetric shrinkage, for untreated, LS treated and cement treated specimens, respectively. The degree of soil shrinkage improved by 13% after 2% LS addition, and a 16% improvement with 2% cement treatment at moisture content equal 0% (Fig 5).

Linear shrinkage

The effect of LS admixture and cement in reducing the linear shrinkage of the remoulded expansive soil is illustrated in Fig 6. It can be observed that for the range of water content tested, there is a reduction in shrinkage when LS admixture and cement are added to the soil, albeit not very significant (≈ 2-5% reduction). While for water contents smaller that 13% both LS and cement yield a comparable shrinkage reduction, for $w > 13\%$ cement seems to be more effective, although the percent reduction difference is small (2-3%). The hydration and cation exchange reactions are the likely reasons for this improvement. Moreover, visual observation of the test specimen after oven drying (Fig 6: inset) indicated significant textural variations and substantial cracking of untreated and cement treated specimens. On the specimen treated with LS a substantial reduction in crack formation was observed. The addition of 2% cement resulted in a loss of cohesion in the soil and thus led to the formation of prominent cracks.

Durability behaviour

Often earth structures are exposed to seasonal climatic changes of moisture caused by periods of rainfall and drought that can induce wetting and drying cycles. It is thus relevant to evaluate the performance of LS in controlling the durability of the soil in repeated wetting and drying cycles, e.g. minimising potential collapse upon wetting. A pictorial illustration of the specimens throughout the test is shown in Fig 7. The tests were conducted in accordance with ASTM D559 (ASTM, 2003) but wetting-drying cycles were continued only to the end of 4th cycle because all test specimens failed. A simple procedure was developed to measure the loss of soil mass at the end of each cycle. This procedure involved measuring the mass of a specimen before and after each cycle. Broken pieces of soil were carefully removed before measurements were recorded. Fig 7 showed that the untreated soil exhibited a rapid mass loss of material during the wetting cycles, i.e. 33% and 71% mass loss was recorded for the 1st and 2nd wetting cycles, respectively. Furthermore, after oven-drying the untreated specimen it completely disintegrated (Fig 7), so the test was stopped at the end of the second cycle. It is likely that the attractive forces between the untreated soil particles were so weak (i.e. Van der Waal forces) that capillary pressure reduction during a wetting phase caused the untreated specimen to disintegrate significantly.

The addition of 2% LS increased the resistance of the soil to repeated wetting and drying such that at the end of the 1st cycle only 7.7% of mass was lost; this was a 76.7% improvement in the durability of the soil (Fig 7). However, at the end of the 2nd cycle, a 32.4% of mass was lost. The untreated soil had completely disintegrated at this stage, indicating that the addition of 2% LS improved the wetting-drying durability of the soil at the end of the 2nd cycle by 67.6%. It is most likely specimen treated with 2% LS adsorbed less moisture leading to capillary pressure reduction during wetting, i.e. the addition of LS contributed to a more stable pore structure and enhanced its ability to withstand repeated wetting and drying. The soil treated with 2% cement experienced the least loss of mass under wetting-drying conditions, with only 2.5% and 9.2% mass loss at the end of the 1st and 2nd cycles, respectively. It is likely that the addition of cement provided addition chemical bonding between the clay minerals that offered resistance against the capillary pressure exerted on the soil pore walls.

The durability against freeze and thaw cycles of the untreated and chemically treated specimens were evaluated by the percentage mass loss, the percentage of volumetric change and the percentage of moisture variation are illustrated in Fig 8a-d. The results of the percentage mass loss are presented in Fig 8a. It was observed through visual inspection that all specimens developed ice crystals during the freezing stage accompanied with volume change. With a continuous decrease in temperature, all specimens developed cracks especially at the edges resulting in substantial spalling of specimens as test progressed, more significant was the specimen stabilized with 2% cement. This specimen experienced the highest level of mass loss and the durability test was stopped after the 6th cycle (Fig 8a) due to significant mass loss.

There was a substantial improvement in resistance to temperature variation for the specimen treated with 2% LS. The most striking observation is that the LS treated soil lost only 3-4% of its mass while the untreated specimen experienced a 7% loss in mass at the end of the 12th cycle.

In terms of the percentage volume change, the maximum change for all specimens occurred at the end of the 3rd cycle with the untreated specimen exhibiting the most significant change in volume from the 1st to the 3rd cycle. For untreated soil, the volume increased by almost 15.9% as opposed to 11.2% and 6% for specimens treated with 2% LS and cement, respectively (Fig 8b). After the 3rd cycle, the volume change in each specimen decreased with increasing number of cycles until the 9th cycle. The progressive decrease in specimen volume was described as the "fatigue" of volume change by Chen (1988). While this is clearly observed towards the end of the test (i.e. the 9th cycle) for the untreated and LS treated specimens, this phenomenon is less obvious for the cement treated specimen (Fig. 8b). This is because cement decreased the swelling tendency of the soil more significantly. When the decreasing dry density due to repeated freezing and thawing reaches the "critical dry density" (where swelling and shrinkage equalizes) swelling, shrinkage, and dry density become stable and thus the volume of soil is stable irrespective of changes in environmental conditions such as temperature. The maximum volume change recorded for untreated and 2% LS treated specimens was 7.0% and 4.6%, respectively.

The freezing cycles had a small effect on soil shrinkage behaviour (Fig 8c); shrinkage recorded for the untreated soil during the 1st cycle was 4.7% but it decreased to 3.8% at the 9th cycle, whereas the soil treated with 2% LS decreased in shrinkage from 3.8 to 3%. This behaviour could be attributed to the decreasing dry density of the soil during freezing stage. As the decreasing dry density reaches a critical value, further freezing and thawing had no effect on shrinkage behaviour of the soil.

The moisture content variation at the end of each cycle was also monitored (Fig 8d) and a unique relationship was established between variation in moisture content and change in volume in the specimens observed. Larger variation in specimen volume was observed for those specimens having a greater variation in moisture content. Similarly, the adsorbed moisture contents peaked at the end of the 3rd cycles where maximum swelling occurred in all specimens. The specimen treated with 2% cement exhibited the least variation in moisture content (44%), followed by 2% LS (47%), and 51% for untreated specimens. For LS treated specimen, the hydrophobic component of the admixture likely inhibited the adsorption of moisture by clay minerals; hence justifying the relatively low percent swell observed. For soil stabilised with 2% cement, the reaction mechanisms of hydration and cation exchange altered the mineralogy of the soil, causing it to behave more or less like a silty soil, hence the low adsorbed moisture content which translated into the low percent swell. In addition, the variation in moisture for untreated and LS treated soil attained a state of equilibrium at about the 9th cycle of freezing and thawing.

The unconfined compressive strength (UCS) and soil failure mode

This test was carried out to determine the strength and failure mode of the untreated and chemically stabilized expansive soil. It was evident that the strength of the soil improved after 2% LS was added (265kPa to 285kPa), accounting for a 7.5% improvement. However, the addition of 2% cement increased the strength of the soil from 265kPa to 293kPa, which is a 10.6% improvement. It is interesting to note that although the growth in strength for LS treated specimen was less than that of 2% cement addition, the treated soil maintained its ductility. While all the specimens exhibit a predominantly strain-softening behaviour, the reduction in axial stress at large axial strain is more pronounced for specimen stabilized with cement, which indicate a tendency for brittle failure. The axial strain at failure was 1.78% and 1.82% for untreated and 2% LS treated specimens, respectively whereas the strain at failure was at 1.06% for cement treated specimen (Fig 9). The ductile mode at failure exhibited by the LS treated soil is beneficial for engineering infrastructure. This difference in the type of behaviour, i.e. greater tendency to fail in brittle mode for cement treated soil could be attributed to the formation of large aggregates, strongly bonded particulate matter enabled by the hydration reactions. In contrast, LS stabilisation is mainly due to basal/peripheral adsorption and subsequent coating and binding of soil particles to form a more rigid soil mass (Alazigha et al. 2017). Moreover, detailed triaxial tests on LS treated specimens is important to understand the stress – strain behaviour during monotonic loading condition.

Consolidation characteristics

The data collected during the consolidation tests for untreated, 2% LS, and 2% cement treated soil in this study allowed for the determination of the coefficient of consolidation (C_v), coefficient of compressibility (m_v), and permeability (k_w) of the samples. Conventional one-dimensional consolidation tests were performed on specimens at full saturation with applied vertical stresses of 100, 200, 400, 800, 1500, 2500, and 3500kPa. The Cv response of untreated and chemically treated specimens at various consolidation pressures (Fig 10a) indicated that the Cv generally decreased with increasing consolidation pressure.

The decreasing Cv in the specimens varied slightly in magnitude from one another. For example, for LS treatment, the specimens experienced a fairly rapid initial settlement (2.1x10-06m^2/s under 50kPa to 3.0x10^{-07}m^2/s at 3000kPa) due to a speedy dissipation of pore water pressure. Similarly, the Cv of 2% cement treatment rapidly decreased during initial consolidation pressures i.e. from $2.7x10^{-06} m^2/s$ under 50kPa to $3.2x10^{-07} m^2/s$ at 3000kPa. But this initial rapid settlement was also replaced by a relatively constant Cv despite increasing pressure. In spite of the increasing consolidation pressure (300kPa to 2000kPa), the Cv of the LS treated soil decreased from $3.0x10^{-07} m^2/s$ to $1.0x10^{-07} m^2/s$ only. So, it may be anticipated that after an immediate settlement, the long-term settlement of LS treated clay may be insignificant. This consolidation behaviour exhibited by the treated soil specimens is not typical of clayey soils, implying that the chemical admixtures altered the soil structure in such a way that its consolidation behaviour seemed to resemble that of a silty material.

However, the typical consolidation behaviour of clayey soil was demonstrated by the untreated soil sample. The Cv response of a soft Bangkok clay (Indraratna *et al.,* 1994) is plotted in Fig 10a for comparison. The untreated clayey soils did not experience rapid immediate settlement, suggesting that the LS and cement admixtures altered the soil structure by aggregating particles. This observation was supported by a slight increase in the permeability of treated specimens. The implication of the compressibility behaviour observed for the LS treated soil, is that less time will be required to complete 90% of consolidation compared to the untreated counterpart under the same test conditions.

Fig 10b illustrates the variation of the coefficient of compressibility (m_v) with consolidation pressure of untreated and chemically treated expansive soil. As expected, m_v decreased with increasing consolidation pressure for all specimens, but this decrease in mv was much more evident for the untreated specimen followed by the specimen treated with 2% LS, while the specimen treated with 2% cement experienced the least change in m_v. The implication here is that soil treated with LS will offer greater resistance to compression than untreated soil under the similar conditions. The behavioural differences between the untreated and chemically stabilized specimens can be related to the stabilizing effects of the chemical admixtures. LS and cement admixtures increased the strength of the soil by binding soil particles together thus offering more resistance to volumetric compression. In the samples treated with LS, the intercalation of LS into the diffuse double layer (DDL) of expandable minerals instigated flocculation agglomeration whereas externally adsorbed LS on non-expandable soil minerals (e.g. kaolinite, quartz) also contributed to the agglomeration and subsequent development of soil strength (Alazigha et al. 2017).

The change in soil permeability (k_w) inferred from the consolidation data is shown in Fig 10c. As expected, the kw of all the specimens decreased with increasing consolidation pressure. However, k_w did not change substantially in LS treated specimens with increasing applied pressure compared with untreated specimens. In other words, for any given consolidation pressure, the differences between untreated and LS treated specimens is small, while this is more evident for larger consolidation pressures (>100kPa). For instance, for a consolidation pressure of 50kPa, a variation of 0.26 x 10^{-7}m/s was observed in relation to the untreated specimens, whereas for the cement treated specimen a variation of 0.6 x 10^{-7}m/s was obtained.

The size of the flow channels before and after chemical treatment, as a result of particle aggregation, is one reason for the differences in the k_w values. The untreated sample had the smallest particle size/least connected pore spaces but the increase in particle size after chemical (LS and cement) addition as evident in the SEM and SSA test data (Alazigha et al. 2017) indicated that the chemically stabilised soil has larger but fewer connected pores leading to a slight increase in permeability, especially with the cement admixture (Fig.3). Furthermore, the coefficient of permeability of soil could have been affected by the chemistry of the permeating fluid (LS and cement). With the presence of benzene in LS admixture, kw for treated soil increased slightly as a result of increase in particle size, particle spacing, particle arrangement, and interlayer spacing. Theng (2012) obtained similar results for the coefficient of permeability of clays stabilized with a non-polar fluid (benzene).

Conclusion

In this study, the effectiveness of a non-traditional admixture (LS) was evaluated by performing standard geotechnical laboratory tests on the percent swell, shrinkage, soil durability, uniaxial compressive strength (UCS), compaction characteristics, consolidation characteristics, and the pH of the soil with or without treatment. In some instances, identical test specimens were prepared using 2% cement admixture and tested accordingly for comparison. In general, the results showed significant and consistent changes in the engineering properties of the tested specimens following 2% LS addition. The following conclusions are drawn from this investigation.

1. The percent swell of the soil reduced by 23% for specimens prepared at optimum moisture content and maximum dry unit weight by adding 2% LS. This effect was most significant on “low” expansive soils. In addition, it is recommended that LS treated soil be compacted at optimum characteristics in order to maximum its effects.

2. The presence of 2% LS admixture improved the soil’s resistance to repeated drying and wetting cycles by 77% at the end of the 1st cycle. The freeze-thaw durability of the soil improved in the presence of LS admixture such that it lost only 3.4% of its mass as against 7% for untreated soil at the end of the 12th cycle, whereas 2% cement treated specimen lost 17% of its mass at the end of the 6th cycle.

3. The addition of 2% LS increased the UCS of the soil from 265kPa to 285kPa which was similar to 2% cement application (265kPa to 295kPa). However, the additional benefit of LS treatment is its ability to maintain the soil’s ductility and pH (7.43 to 7.17), unlike

cement that caused brittle failure and significantly increased the pH of the soil from 7.43 and 9.65.

4. The Cv of untreated and chemically treated specimens decreased with increasing consolidation pressure. The fairly rapid initial settlement for treated specimens and the fairly constant Cv suggest that the long-term settlement of LS treated clay may be insignificant compared to the untreated soil. This indicates that less time will be required to complete 90% of consolidation for the LS treated soil than for the untreated counterpart under the same test conditions.

5. The variation of mv indicated that the soil treated with LS will offer greater resistance to compression. The k_w did not change substantially in LS treated specimens at any applied pressure in comparison with untreated soil. This indicates that LS treated soil may be less susceptible to internal erosion problems unlike cement treated specimen that caused significant increase in permeability of the soil.

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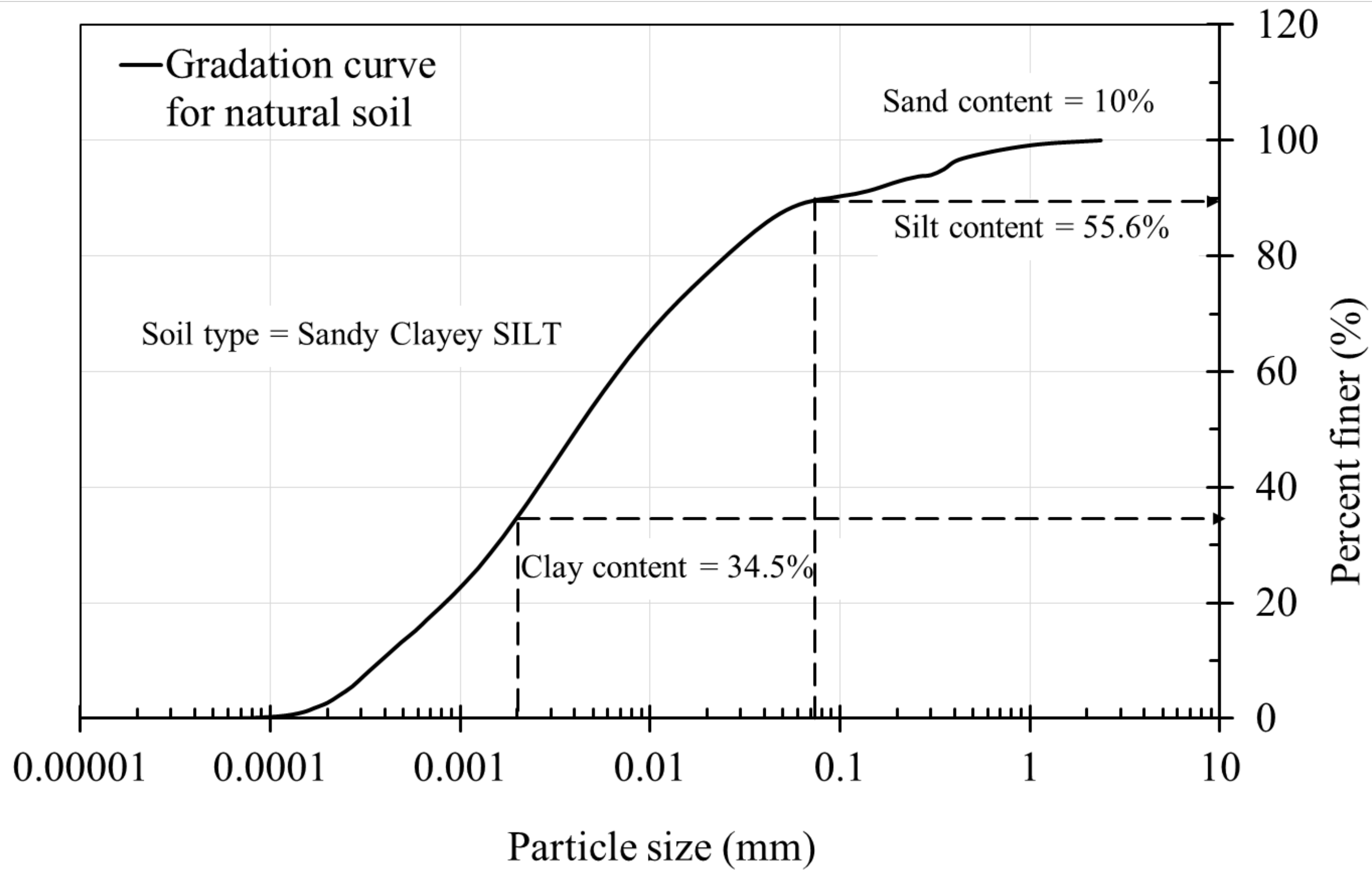

Figure 1: Particle size distribution curve for the natural expansive soil

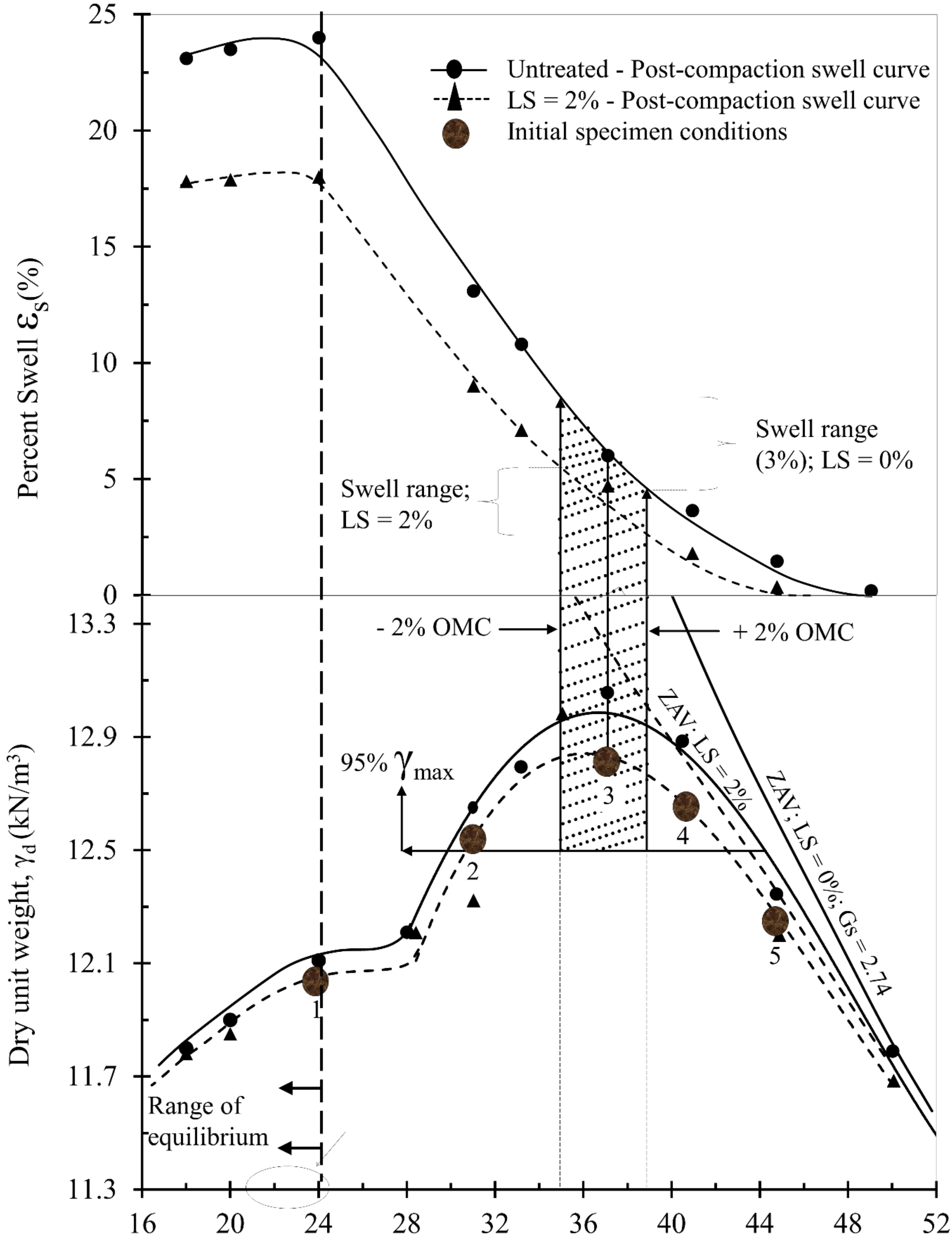

Fig 2: Relationship between compaction characteristics and percent swell

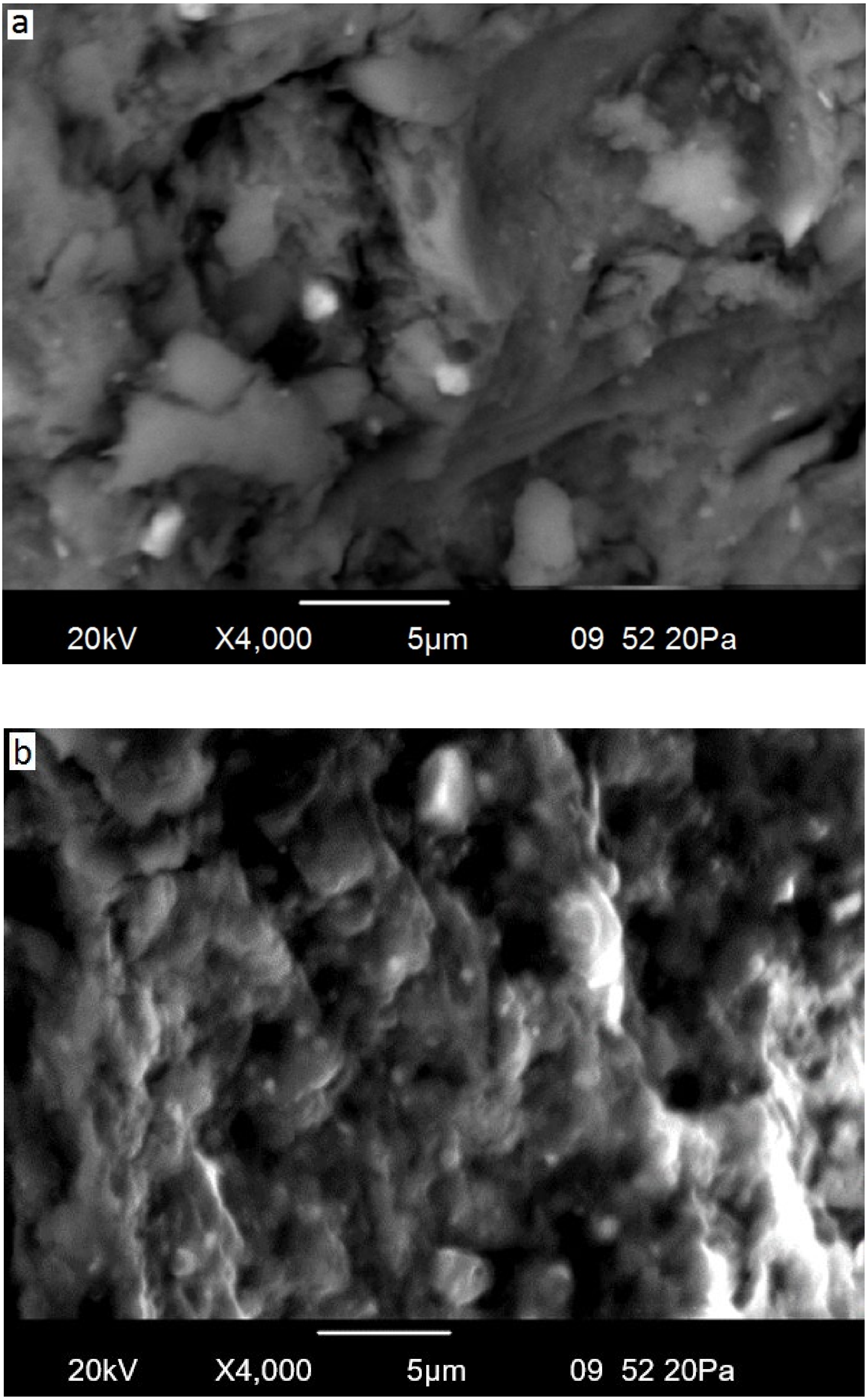

Fig 3: SEM for (a) untreated and (b) LS = 2% treated soil @ w = 36% (Modified after Alazigha et al. (2016))

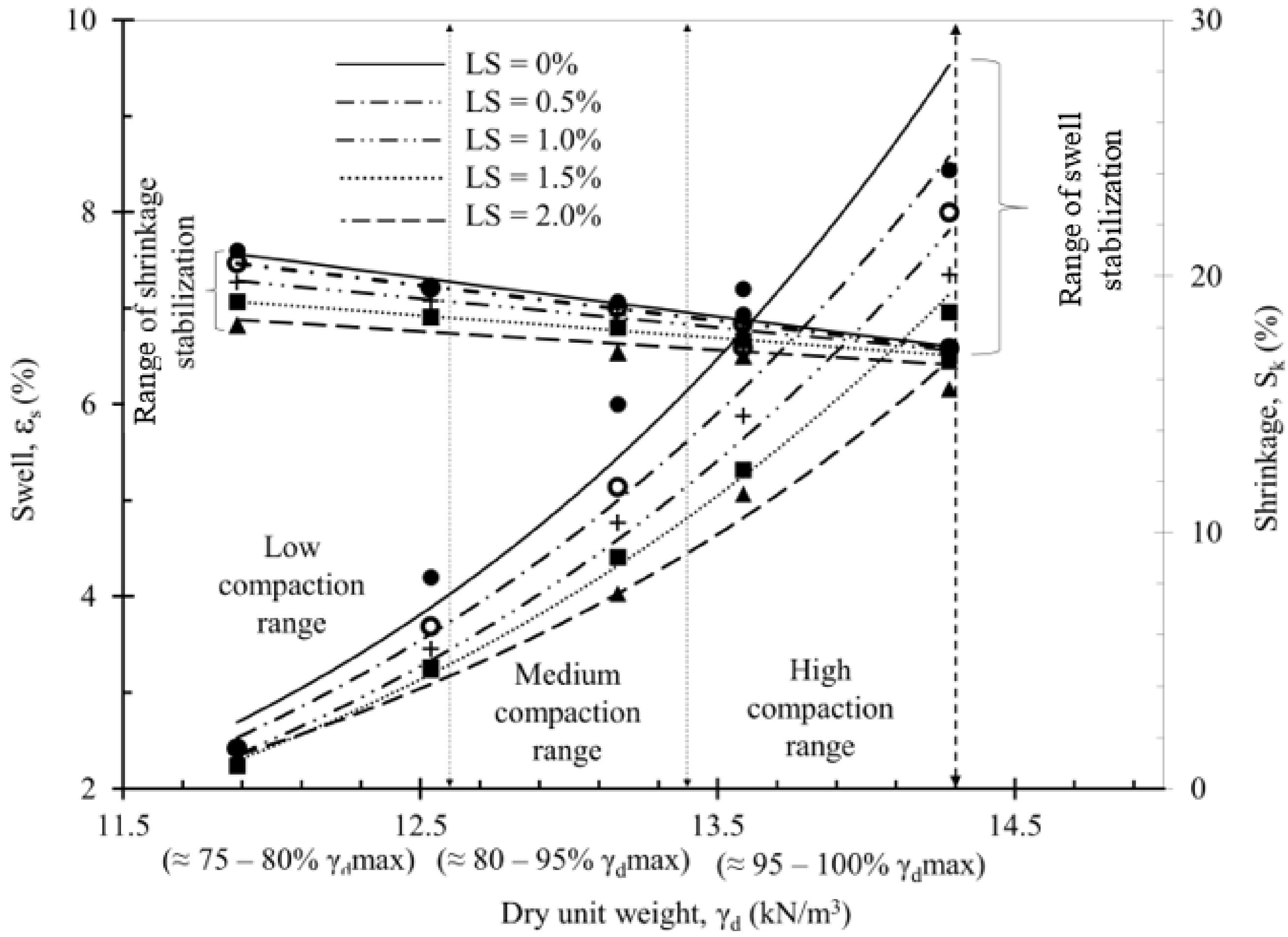

Fig 4: Effects of LS on the initial dry unit weight and shrink-swell relationship

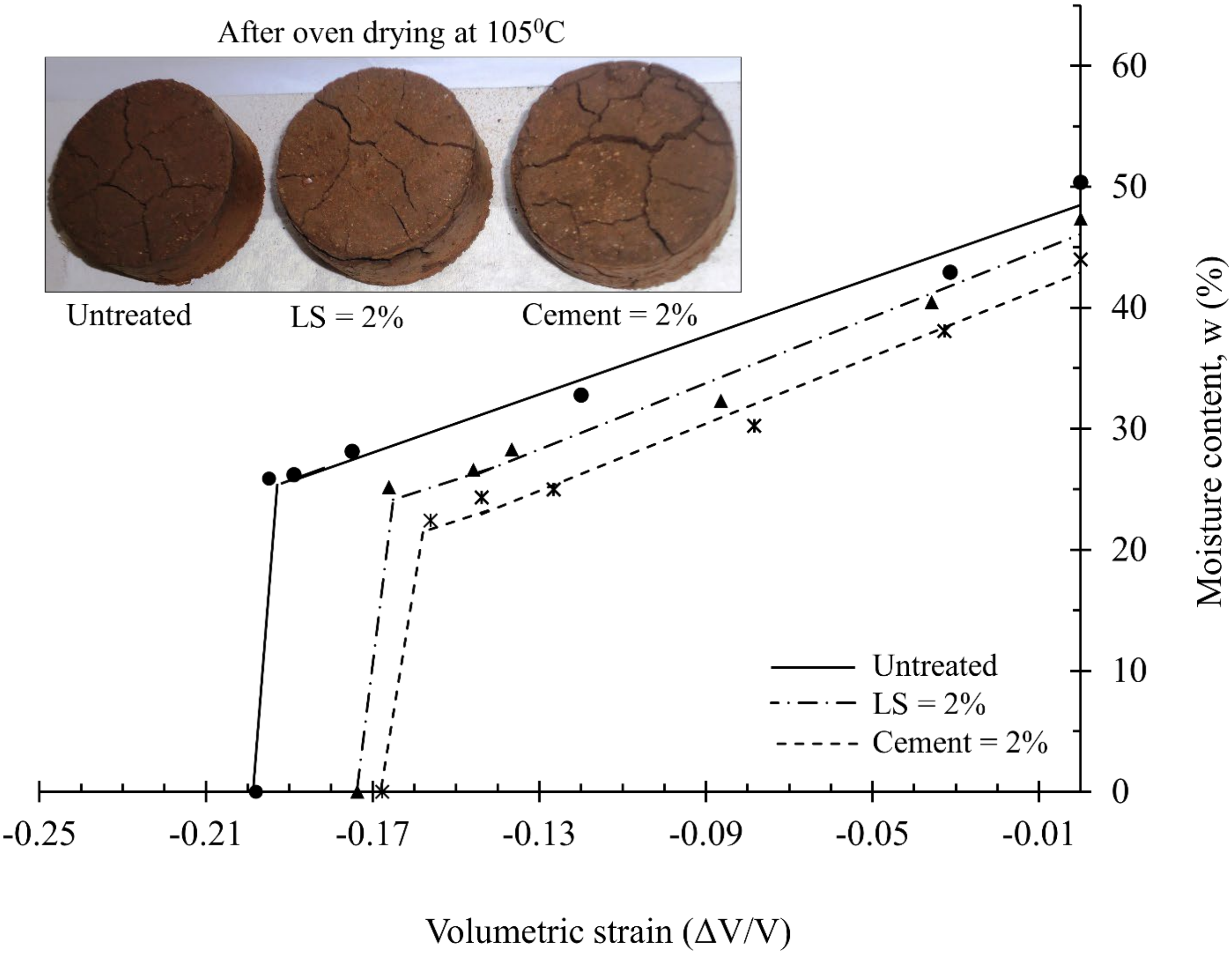

Fig 5: Effect of LS and cement treatment on the volumetric shrinkage of expansive soil

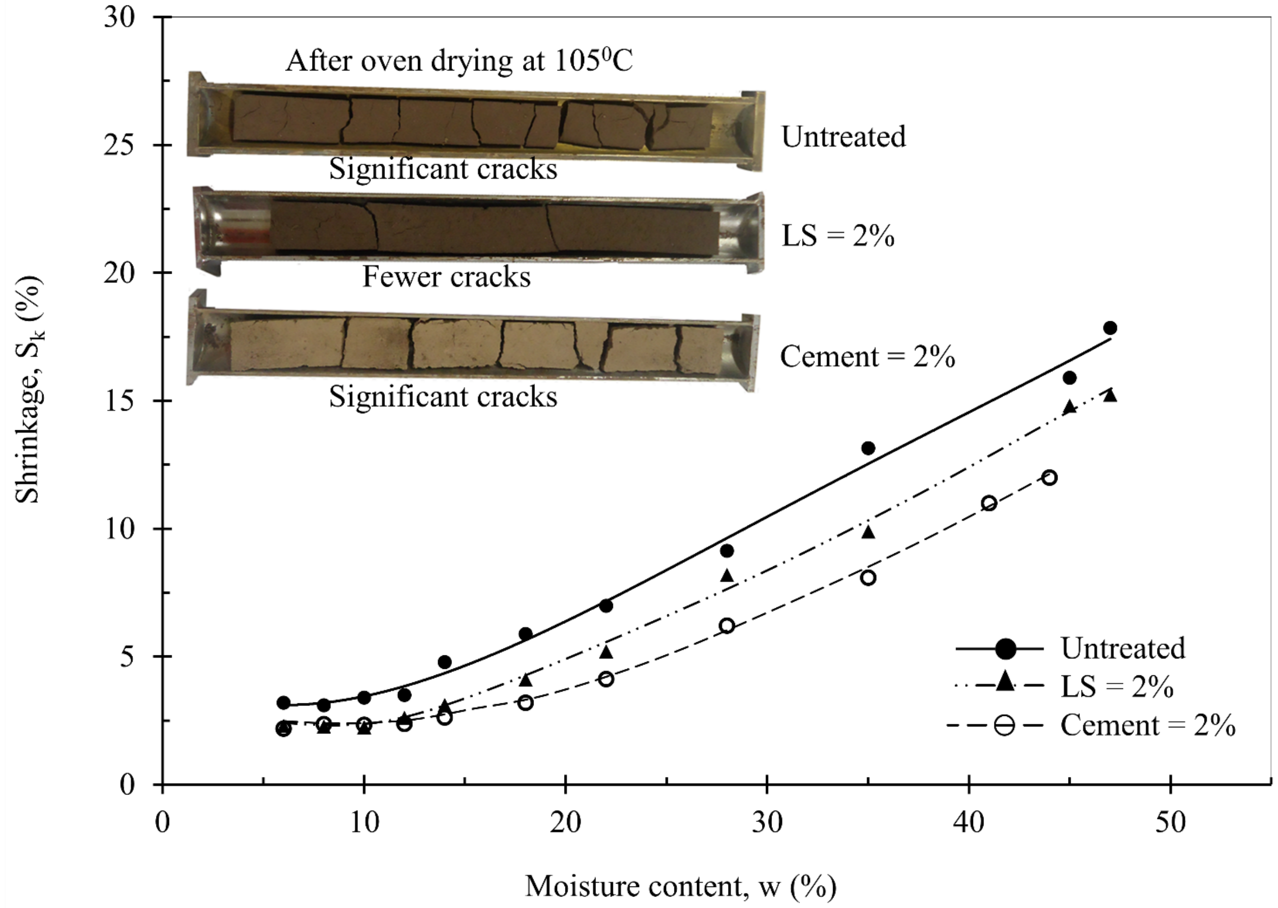

Fig 6: Effect of initial moisture content on shrink-swell behaviour of untreated and chemically treated expansive soil

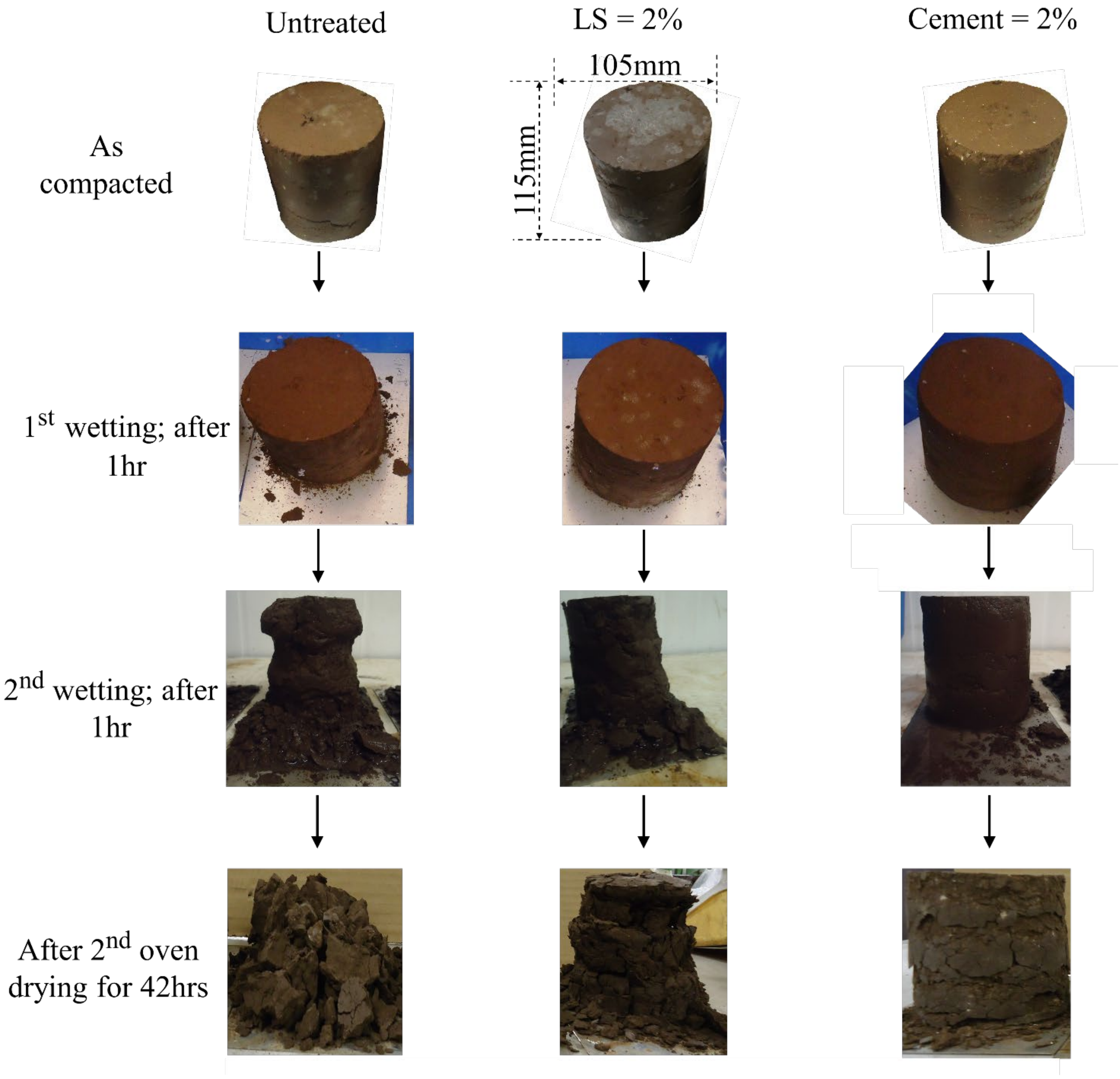

Fig 7: Pictorial illustration of the wetting and drying durability testing of untreated and chemically treated expansive soil

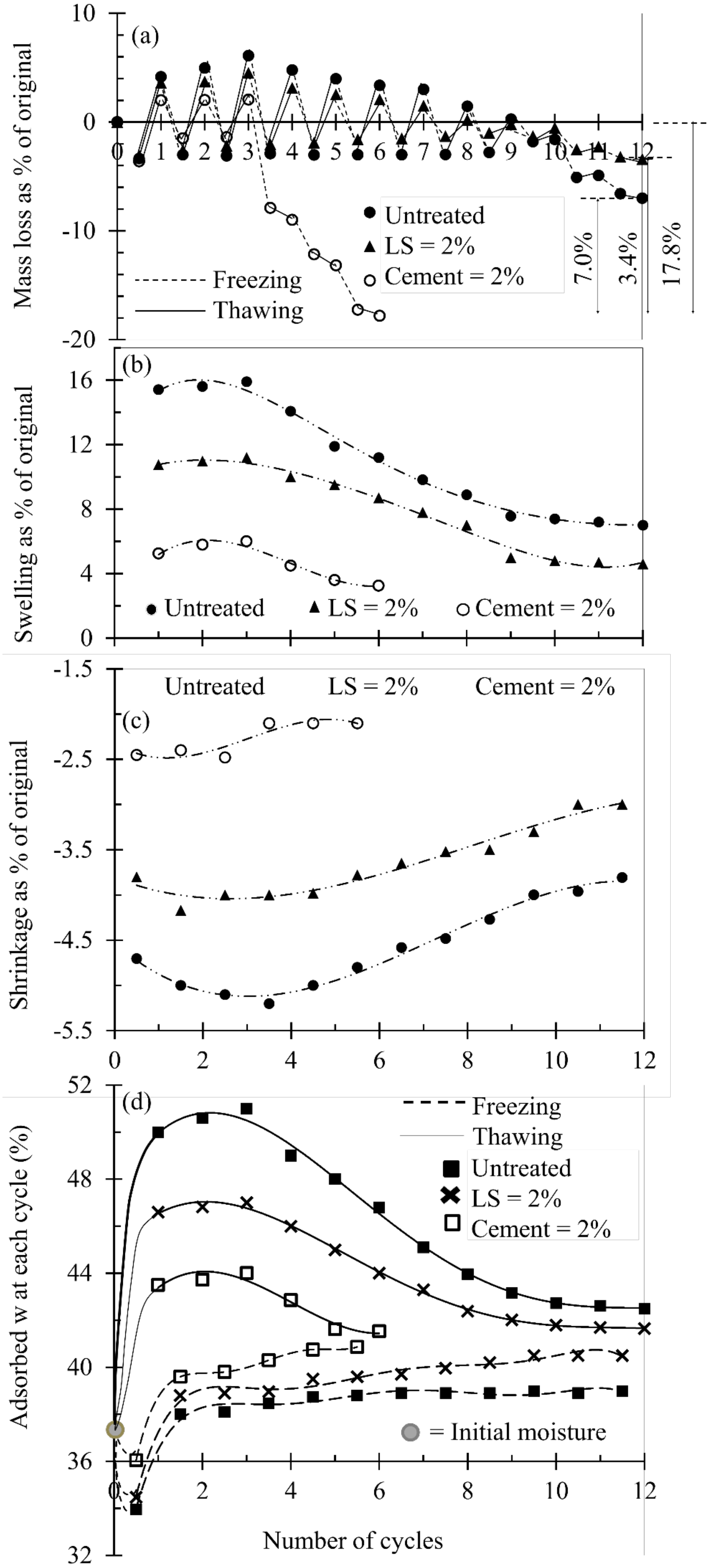

Fig 8(a): Effect of chemical treatment on percentage mass loss in freeze-thaw durability test for soil specimens, (b) volume change behaviour of specimens during thawing cycles, (c) volume change behaviour of specimens during freezing cycles, (d) moisture behaviour during freezing and thawing cycles

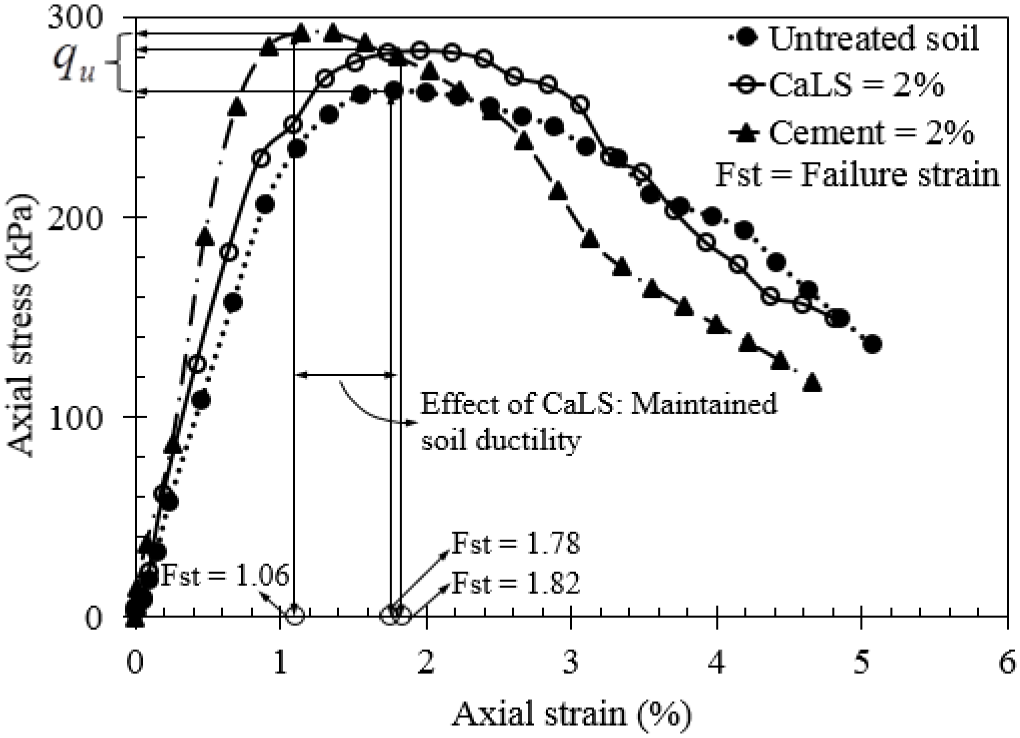

Fig 9: Uniaxial compressive strength and strain at failure for untreated and chemically treated expansive soils

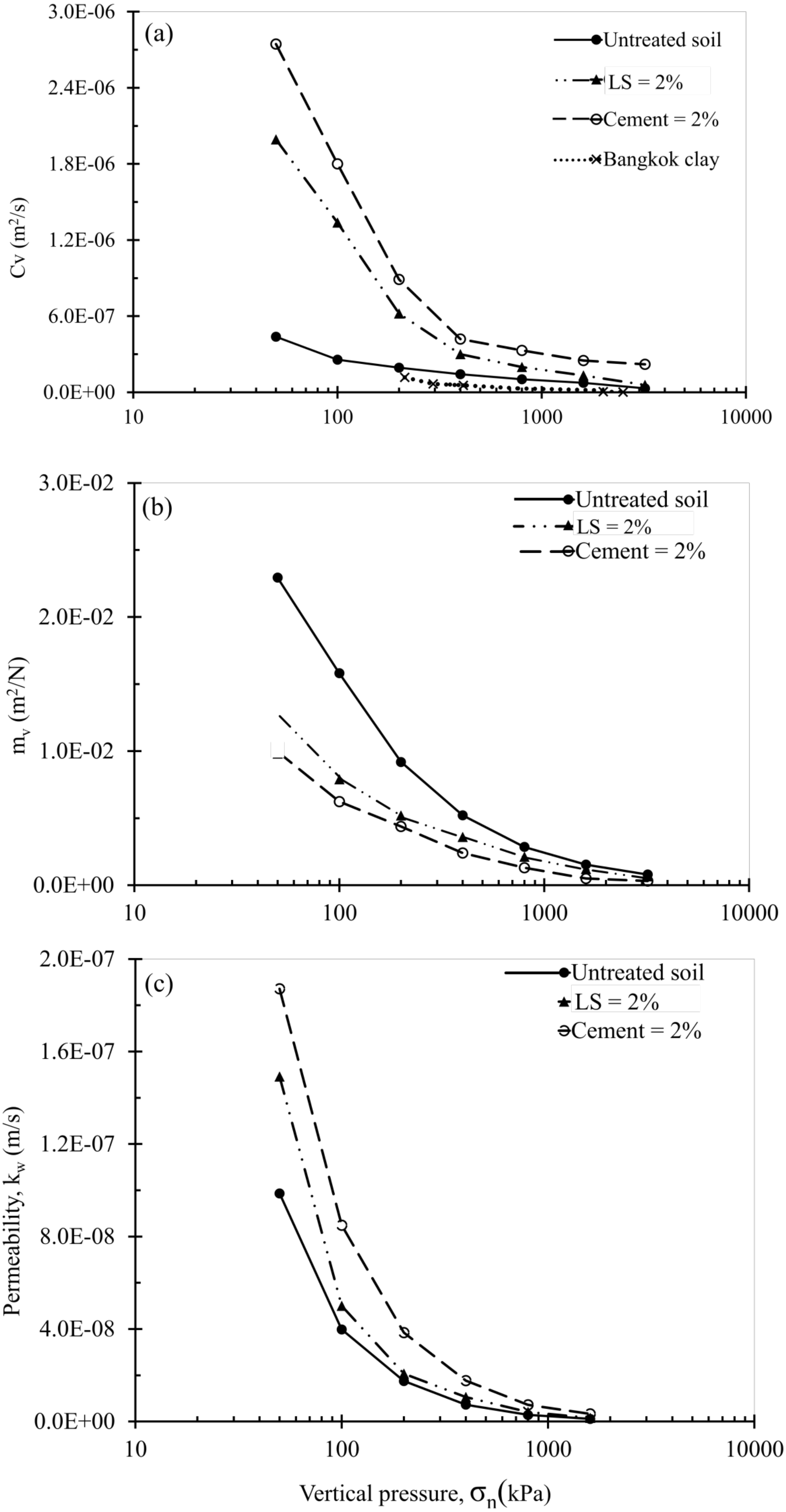

Fig 10: Variation of (a) C_v, (b) m_v, and (c) k_w with vertical pressure for untreated, 2% LS and 2% cement treated expansive soil